Negative refraction and focusing of sound in phononic crystals

J.H. Page[1], A. Sukhovich[1] and Z. Liu[2],
[1] Department of Physics and Astronomy, University of Manitoba, Winnipeg MB Canada R3T 2N2
[2] Department of Physics, Wuhan University, Wuhan 430072 China

Phononic crystals are periodic composite materials with lattice spacings comparable to the wavelength of sound (or ultrasound), and offer some advantages for studying the effects of periodic structure on wave propagation. In this talk I will summarize recent progress using ultrasonic experiments to investigate the focusing of ultrasound by negative refraction [1] in both two- and three-dimensional phononic crystals. In addition to reviewing the underlying mechanisms, experiments on three-dimensional crystals of tungsten carbide or steel beads in water will be described. Experiments that directly demonstrate the negative refraction of an ultrasonic beam in a two-dimensional crystal will also be presented. Our data are well explained using Multiple Scattering Theory, which predicts angles of refraction that are in remarkably good agreement with experiment.

[1] Suxia Yang, J. H. Page, Zhengyou Liu, M. L. Cowan, C.T. Chan and Ping Sheng, *Physical Review Letters,* **93**, 024301:1-4 (2004).

Some studies of subwavelength focusing and open cavity achieved with photonic crystals of negative refraction

Sailing He[1,2], Xianyu Ao[1] and Zhicao Ruan[1]

[1]Joint Research Center of Photonics of the Royal Institute of Technology and Zhejiang University, Zhejiang Universtiy, Hangzhou 310027, China
[2]Division of Electromagnetic Theory, Royal Institute of Technology, Electrum 229, S 16440 Kista, Sweden

Materials or structures exhibiting negative refraction have attracted much attention recently within the community. A well-known example is a negative index material (NIM; also called a left-handed material), whose permeability and permittivity are simultaneously negative over a certain frequency band. Effectively negative permeability and permittivity can be obtained over a certain microwave band for arrays of wires and split-ring resonators. LHMs with simultaneously negative permittivity and permeability have many amazing properties, such as the subwavelength focusing and open cavity. As another important example of negative refraction, a specially designed photonic crystal can also refract light at a negative refraction angle. The performances of subwavelength focusing and open cavity of photonic crystals of negative refraction will be studied and compared with those of LHMs.

A Bloch Wave Model that Describes the Dispersive Effects in Photonic Crystals

B. Lombardet, L. A. Dunbar, *R. Ferrini and R. Houdré,

Institut de Photonique et d'Electronique Quantique, *Laboratory of Optoelectronics of Molecular Materials, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland.

Phenomena such as negative refraction, high dispersion and self-collimation have been numerically modelled and experimentally observed in Photonic Crystals (PhCs). However, as yet, little work has been published on the physical intepretation of these effects in PhCs. We will present an original description based on the Fourier transform of electromagnetic Bloch waves that are the standard representation of the optical field propagating in periodic media. Initially, we will consider an electromagnetic Bloch wave propagating in a PhC and demonstrate that it can be decomposed into a series of partial-electromagnetic plane waves. The properties of these constitutive plane waves will be discussed, and their individual contributions to the total energy and group velocity of the global Bloch wave detailed. The validity of the decomposition will be shown for TE and TM waves in both the one- and two-dimensional case.

This original approach brings an intuitive understanding to light propagation in PhCs, in particular it gives a continuous description of the light properties when moving from a homogenous to a strongly modulated medium. Moreover, it also resolves inconsistencies resulting from the artificial band folding for vanishing modulations, as were originally pointed out by *Notomi* [1]. Using the model we will describe the unusual properties of light propagation in PhCs. Finally, we will discuss these compare with similar properties seen in left-handed materials.

[1] M. Notomi, *Physical Review B*, **62**, 10696 (2000).

Anomalous refractive effects at the interface of two-dimensional PCs

Stavroula Foteinopoulou [1,2] and Costas M. Soukoulis [1]
[1] Ames Laboratory US-DOE and Department of Physics and Astronomy, Iowa State University, Ames, Iowa, 5001
[2] current address: Laboratoire de Physique du Solide, Univ. of Namur, Belgium.

Photonic crystals (PCs) can enable left-handed (backwards wave) propagation when certain conditions are met [1]. Nonetheless, negative refraction at PC interfaces is neither a prerequisite nor a manifestation of backwards wave propagation [2]. We study systematically the refractive behavior of two-dimensional PCs with the Finite Difference Time Domain (FDTD) method [3]. We have identified four distinct cases for which a negatively refracted beam is present. Nonetheless, only in one of these cases the negatively refracted beam is a backwards wave. We analyze the different mechanisms that can lead to a negatively refracted beam with the wave vector diagram formalism. We found that such formalism is general, and always leads to a correct prediction/interpretation of the refracted beam(s). Finally, we study the phase and "rightness" of EM wave propagation in PCs with a low index modulation, and make a comparison with the high-index modulation cases.

[1] S. Foteinopoulou, E. N. Economou, and C. M. Soukoulis, Phys. Rev. Lett. **90**, 107402 (2003). [2] S. Foteinopoulou and C. M. Soukoulis, Phys. Rev. B **67**, 235107 (2003). [3] S. Foteinopoulou and C. M. Soukoulis, cond-mat/0403542.

3D Opal Photonic Crystals Grown on Patterned Silicon Platforms#

F. Jonsson[1*], J. Ye[2], S. Arpianen[3], R. Zentel[2], J Ahopelto[3] and C.M. Sotomayor Torres[1]
[1] Tyndall National Institute, University College Cork, Lee Maltings, Cork, Ireland
[2] Institute of Organic Chemistry, University of Mainz, Duesbergweg 10-14, D-55099 Mainz, Germany
[3] VTT Centre for Microelectronics, P.O. Box 1208, FIN-02044 VTT, Finland

Silica and PMMA opals have been grown on patterned silicon substrates as a step towards integration of 3D light emitters and 2D waveguides on a single chip The main result is that opal growth has been achieved with a high degree of site selectivity, using capillary forces combined with suitable substrate designs and surface preparation.

Optical microscope images demonstrate the spatial selectivity on large scale with dye loaded PMMA. For further details both, PMMA and silica opals, are examined with scanning electron microscopy.

The opals grown in the structured silicon have been characterized by far-field and near-field spectroscopy and show clearly Bragg reflections and luminescence commensurate with the number of layers, the crystal order and the transitions expected in the emitting centers in a photonic crystal environment.

Optical spectroscopy results data and possible integration prospects will be discussed.

Work supported by the Science Foundation Ireland and the EU IST FET project Nr. 510162 (PHAT).
* Present address: Dept Physics, University of Southampton, Southampton, UK.

All-Fiber-Optic Photonic Crystal Light Emitter

Yong-Hee Lee and In-Kag Hwang
Department of Physics, KAIST, Daejeon 305-701, Korea

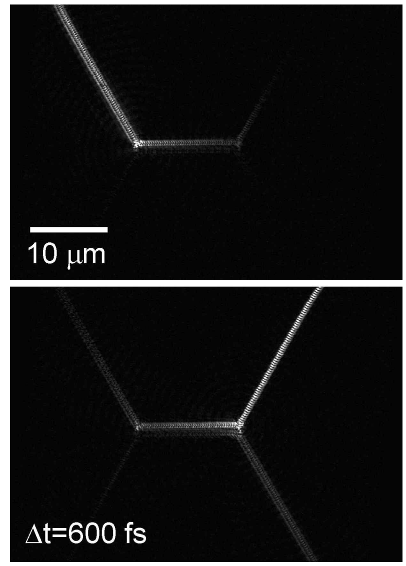
Efficient output coupling from photonic crystal light source has long been an issue toward practical stand-alone light source. We present the simple and effective scheme for the direct evanescent coupling with a tapered optical fiber, where both optical pumping and output collection are carried out through the same fiber. The sharply-curved tapered fiber was positioned above the three-defect laser cavity with an air gap less than 1 μm. 980 nm pump light was injected into the fiber though WDM coupler and transferred to the laser cavity. The laser output was coupled back to the fiber with the same coupling efficiency in the both directions.

Stable single mode lasing was observed with the low threshold of 35 μW. The output coupling efficiency was estimated to be as high as ~70% in the experiment, close to the theoretical value of 84% from FDTD simulation. This compact, stand-alone, fiber-coupled ultimate light source may find its immediate applications in quantum optics and optical communications.

Pulse tracking in photonic crystal devices by near-field microscopy

R.J.P. Engelen[1], Y. Sugimoto[3], J.P. Korterik[2], N.F. van Hulst[2],
N. Ikeda[3], K. Asakawa[3], L. Kuipers[1,2]
[1)] FOM Institute for Atomic and Molecular Physics, Amsterdam, The Netherlands
[2)] MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
[3)] The Femtosecond Technology Research Association (FESTA), Tsukuba, Japan

The time-resolved propagation of femtosecond pulses in a composite photonic crystal device is visualized with a near-field microscope. This way truly guided light is mapped with sub-wavelength resolution. With our time-resolved method, we track the pulses as they propagate through a photonic crystal device composed of straight waveguides, 60-degree bends and a directional coupler. The near-field data allows the unambiguous quantification of the losses, reflection and transmission of the device elements individually. Novel reciprocal space movies elucidate the dynamic response of the various photonic elements and the coupling between them. The images show two snapshots of the time-resolved near-field measurements.



Near-field Imaging and Manipulation of Light in Photonic Crystals

A.F. Koenderink, B.C. Buchler, M. Kafesaki, and V. Sandoghdar
Laboratory of Physical Chemistry, Swiss Federal Institute of Technology (ETH), CH-8093 Zurich, Switzerland

We use Scanning Near-field Optical Microscopy to image directly the spatial extent of light in photonic crystal microcavities and waveguides. We show that the analysis of such field maps reveals important information about the deviations of the crystal structure from its nominal fabrication design [1, 2]. Our findings emphasize that the performance of photonic crystal structures is very sensitive to various design parameters and that a very high degree of control is necessary in the fabrication.

In addition to imaging, we discuss how a near-field probe can be used to manipulate the resonance of a photonic crystal microcavity. By performing Finite Difference Time Domain (FDTD) as well as perturbative analytic calculations, we demonstrate that it is possible to shift the resonance of a microcavity while maintaining a high quality factor [3]. We discuss prospects of this technique for opto-mechanical switching of photonic crystals. Furthermore, we will present results on the modification of spontaneous emission of a nanoscopic emitter placed in the near field of a two-dimensional photonic crystal slab [4].

[1] P. Kramper, et al., *Opt. Lett.* **29**, 174 (2004).
[2] B. C. Buchler, et al., *IEICE Trans.Electron.* **E87-C**, 371 (2004).
[3] A. F. Koenderink, M. Kafesaki, B. C. Buchler, V. Sandoghdar, *submitted*.
[4] A. F. Koenderink, et al., *in preparation*.

Zn and ZnO opals for PBG applications

C. López, B.H. Juárez, D. Golmayo, P.D. García and A. Blanco
Instituto de Ciencia de Materiales de Madrid (CSIC); C/ Sor Juana Inés de la Cruz 3,
28049 Madrid, Spain

Metals are increasingly gaining terrain in the area of PBG. Thus, methods to produce metallic structures compatible with well-known synthetic routes employed for dielectrics are nowadays demanded.

Zn is here taken as an example and the growth of the metal inverse opals by electrodeposition on semiconducting substrates is shown [1]. On the other hand the growth of ZnO, a material of wide application spectrum, is demonstrated by a modified MOCVD method. Furthermore, in addition to its optical properties, its electrical properties make it a material with potential use as electrode for the growth of metallodielectric opals.

The challenge is now to combine the growth of these two materials and others (organic and inorganic, metals and semiconductors) to produce well tuned heterostructures with desired properties.

[1] B.H. Juárez et al., *J. Phys. Chem B*, **108**, 16708 (2004).

Dispersion compensation in 40-Gb/s optical transmission by using coupled-cavity-type photonic crystals

Toshihiko FUKAMACHI[1, 2, 3], Kazuhiko HOSOMI[1, 2, 3], Toshiki SUGAWARA[3], Nobuhiko KIKUCHI[3], Toshio KATSUYAMA[1, 2] and Yasuhiko ARAKAWA[1]
[1]NCRC, I IS, Univ. of Tokyo 4-6-1, Komaba, Meguro-ku, Tokyo 153-8505, Japan
[2]OITDA, Tokyo, Japan, [3]CRL Hitachi, Ltd., Tokyo, Japan

Dispersion compensation by photonic crystal coupled-cavity waveguides (PhC CCWs) was investigated experimentally, and we demonstrated for the first time that the PhC can compensate for dispersion in a 40-Gb/s non-return-to-zero optical transmission. In this experiment, we stacked ten one-dimensional CCWs, which consist of SiO_2/Ta_2O_5-thin films, and optical signals were transmitted into these CCWs three times [1]. As a result, a well-defined eye pattern was obtained at a distance of 4.5 km for a single-mode fiber (Fig. 1). However, it closed without the CCWs. This indicated that the CCWs compensated for a dispersion of more than 60 ps/nm. This result will enable a drastic downsizing in the dispersion compensator by PhC, compared with one used in conventional optical communication.

This work is supported by OITDA contracted with NEDO and MEXT IT program.

[1] T. Fukamachi *et al.*, PECS-V, Th-P26, p206 (2004).

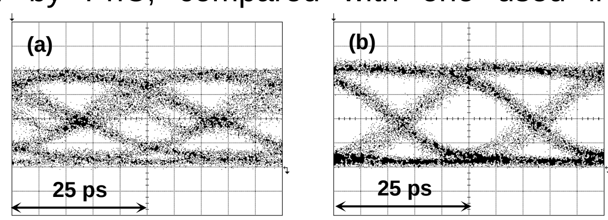


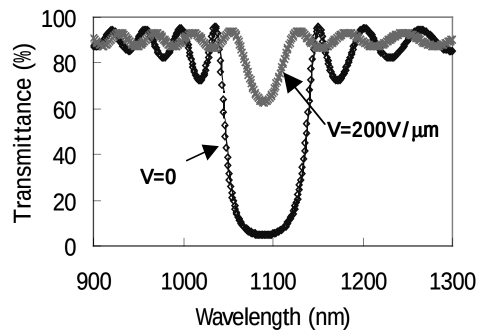
Fig. 1 Eye patterns (a) after transmission over the distance of 4.5 km and (b) after compensating for the dispersion.

Ultra-fast optical switch using 1D polymeric photonic crystals

R. Katouf(1), T. Komikado(2), M. Itoh(1), T. Yatagai(1) and S. Umegaki(2),
(1) Institute of Applied Physics, University of Tsukuba, Tennodai 1-1-1, Tsukuba, Ibaraki, Japan.
(2) Faculty of Science and Engineering, Keio University, Yokohama, Japan.

Photonic Crystals for optical applications have been attracting increasing interest in recent years but polymers are seldom used in the fabrication of photonic crystals due to their low refractive index. However, recently we reported the fabrication of a 1D photonic crystal made by spin coating of polymers dissolved in solvent [1]. This method is simpler and has a low cost.

In this paper we report the simulation and fabrication results of ultra-fast optical switching at 1064nm using one-dimensional nonlinear polymeric photonic crystals, which have been fabricated by stacking alternating periodic multilayers of Poly(vinyl carbazole) PVK as the high refractive index layer and Poly(acrylic acid) PAA doped Disperse Red1 DR1 as the low refractive index layer.



We observed that the band gap became narrower due to the electro-optic effect in the low refractive index layers. The calculated transmission at 1064nm changed from 93% before applying the voltage (V=0) to 10% during application (V=200V/µm) as shown in the figure.

[1] R. Katouf et al, *65th Japan applied physics conference*, (2004).

Ultrafast all-optical control in photonic crystal cavities using nonlinear absorption

C.-S. Kee*, Y. L. Lee, D.-K. Ko, and J. Lee
Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea
H.-G. Choi, J.-E. Kim, and H. Y. Park
Department of Physics, Korea Advanced Institute of Science and Technology, Daejon 305-701, Republic of Korea

Optical nonlinearities of semiconductors can offer interesting effects on the properties of photonic crystals based on semiconductors [1]. In particular, the nonlinear absorption such as two-photon absorption can give an opportunity to control optically the properties of semiconductor photonic crystals. Moreover, a fast response time of free carriers generated by two-photon absorption can offer rapid control in semiconductor photonic crystals. Thus the nonlinear absorption can be useful for achieving ultrafast all-optical control in photonic crystal devices. In this presentation, we theoretically show that the properties of AlGaAs photonic crystal cavity can be optically controlled by two-photon absorption. The measured free carrier induced refractive index change as a function of pump power [2] was employed in the calculations. The resonant wavelength λ_{re} exhibits a blueshift when the pump power increases. The modulation depth, defined as $|(T_{\text{pump-off}} - T_{\text{pump-on}}) / T_{\text{pump-off}}|$, can reach about 90 % when the pump power is 2.5 mJ/cm^2. The modulation time is predicted to be faster than 10 ps.

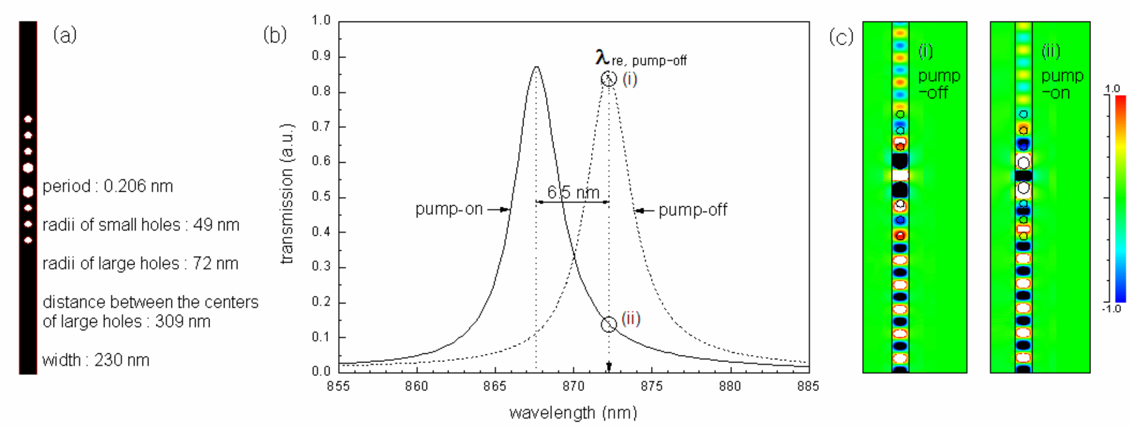


Figure 1. Transmission spectra for TM mode whose magnetic field is parallel to the axis of a hole through AlGaAs photonic crystal cavity (a) and spatial distributions of magnetic filed for $\lambda_{\text{re, pump-off}}$ when the pump laser with power of 2.5 mJ/cm^2 is off and on (b). Schematic top view of AlGaAs photonic crystal cavity and its structural parameters are shown in (c).

Reference

*Email: cskee@gist.ac.kr

[1] A. Hache and M. Bourgeois, *Applied Physics Letters,* **77**, 4089 (2000).
[2] A. D. Bristow, D. O. Kundys, A. Z. Garcia-Deniz, J. P. R. Wells, A. M. Fox, M. S. Skolnick, D. M. Whittaker, A. Tahraoui, T. F. Krauss, and J. S. Roberts, *Journal of Applied Physics,* **96**, 4729 (2004).